PATENT COOPERATION TREATY

PCT

NOTIFICATION OF THE RECORDING OF A CHANGE

(PCT Rule 92bis.1 and Administrative Instructions, Section 422)

From the INTERNATIONAL BUREAU

To:

GILSON, David, Grant
Spoor and Fisher
P.O. Box 41312
2024 Craighall
AFRIQUE DU SUD

Date of mailing (day/month/year) 21 December 2000 (21.12.00)	
Applicant's or agent's file reference W/D/107	**IMPORTANT NOTIFICATION**
International application No. PCT/IB99/01002	**International filing date** (day/month/year) 03 June 1999 (03.06.99)

1. The following indications appeared on record concerning:

[X] the applicant [ ] the inventor [ ] the agent [ ] the common representative

Name and Address	State of Nationality	State of Residence
DE BEERS INDUSTRIAL DIAMOND DIVISION (PROPRIETARY) LIMITED SEO Building Corner Crownwood & Booysens Reserve Roads Theta 2001 JOHANNESBURG South Africa	ZA	ZA
	Telephone No. +27-11-374-6011	
	Facsimile No. +27-11-374-6841	
	Teleprinter No.	

2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:

[ ] the person [X] the name [ ] the address [ ] the nationality [ ] the residence

Name and Address	State of Nationality	State of Residence
DE BEERS INDUSTRIAL DIAMONDS (PROPRIETARY) LIMITED SEO Building Corner Crownwood & Booysens Reserve Roads Theta 2001 JOHANNESBURG South Africa	ZA	ZA
	Telephone No. +27-11-374-6011	
	Facsimile No. +27-11-374-6841	
	Teleprinter No.	

3. Further observations, if necessary:

4. A copy of this notification has been sent to:

[X] the receiving Office
[ ] the International Searching Authority
[X] the International Preliminary Examining Authority
[ ] the designated Offices concerned
[X] the elected Offices concerned
[ ] other:

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Maria Victoria CORTIELLO Telephone No.: (41-22) 338.83.38

M·H

.TENT COOPERATION TRE.. Y

From the INTERNATIONAL BUREAU

To:

Assistant Commissioner for Patents
United States Patent and Trademark Office
Box PCT
Washington, D.C.20231
ÉTATS-UNIS D'AMÉRIQUE

in its capacity as elected Office

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

Date of mailing (day/month/year) 19 January 2000 (19.01.00)	
International application No. PCT/IB99/01002	**Applicant's or agent's file reference** W/D/107
International filing date (day/month/year) 03 June 1999 (03.06.99)	**Priority date** (day/month/year) 08 June 1998 (08.06.98)
Applicant SUSSMANN, Ricardo, Simon et al	

1. The designated Office is hereby notified of its election made:

[X] in the demand filed with the International Preliminary Examining Authority on:

08 December 1999 (08.12.99)

[ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was
[ ] was not

made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Yolaine CUSSAC Telephone No.: (41-22) 338.83.38

PATENT COOPERATION TREATY

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

PCT

To:

GILSON, David, Grant
Spoor and Fisher
P.O. Box 41312
2024 Craighall
AFRIQUE DU SUD

SPOOR AND FISHER
31 JUL 2000
SEEN
MAIL

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Rule 71.1)

	Date of mailing (*day/month/year*) 19.07.2000	
Applicant's or agent's file reference W/D/107	**IMPORTANT NOTIFICATION**	
International application No. PCT/IB99/01002	International filing date (*day/month/year*) 03/06/1999	Priority date (*day/month/year*) 08/06/1998
Applicant DE BEERS INDUSTRIAL DIAMOND DIVISION (PROPRIETARY)		

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.

2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.

3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. **REMINDER**

The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices) (Article 39(1)) (see also the reminder sent by the International Bureau with Form PCT/IB/301).

Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

For further details on the applicable time limits and requirements of the elected Offices, see Volume II of the PCT Applicant's Guide.

Name and mailing address of the IPEA/	Authorized officer
European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	De Caevel, J-M Tel.+49 89 2399-2557

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference W/D/107	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/IB99/01002	International filing date *(day/month/year)* 03/06/1999	Priority date *(day/month/year)* 08/06/1998
International Patent Classification (IPC) or national classification and IPC G01T1/26		
Applicant DE BEERS INDUSTRIAL DIAMOND DIVISION (PROPRIETARY)		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 5 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 2 sheets.

3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☐ Certain observations on the international application

Date of submission of the demand 08/12/1999	Date of completion of this report 19.07.2000
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Rabenstein, W Telephone No. +49 89 2399 2450

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/IB99/01002

I. Basis of the report

1. This report has been drawn on the basis of (*substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments.*):

Description, pages:

1-9 as originally filed

Claims, No.:

1-14 with telefax of 07/07/2000

Drawings, sheets:

1/1 as originally filed

2. The amendments have resulted in the cancellation of:

- ☐ the description, pages:
- ☐ the claims, Nos.:
- ☐ the drawings, sheets:

3. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

4. Additional observations, if necessary:

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/IB99/01002

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-14
	No:	Claims	
Inventive step (IS)	Yes:	Claims	1-14
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-14
	No:	Claims	

2. Citations and explanations

see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET

International application No. PCT/IB99/01002

1 **Re Item V**

1.1 Reference is made to the following document:

D1: WO 97 00456 A (IMPERIAL COLLEGE ;HASSARD JOHN FRANCIS (GB); GODDARD ANTONY JOHN H) 3 January 1997 (1997-01-03)

1.2 The application relates to a detector for ionizing radiation comprising diamond as detector material. Such detectors are known and generally comprise a diamond layer sandwiched between two electrodes (see for example D1). A problem with the known detectors is that they do not allow to detect different types of radiation or different parameters of one kind of radiation, as they are generally optimized for the type of radiation to be measured. In one arrangement of D1, it is possible to detect at the same time slow and fast neutrons by using two separate detectors and covering one by a slow neutron filter.

The object underlying the present invention is to create a single device allowing simultaneous measurement of different types or different parameters of radiation. This is achieved by providing at least two diamond layers of different thicknesses on a common electrode. The only document relating to the detection of different parameters of radiation is D1, but this document requires two separate detectors and an additional filter. The use of diamond layers of different thicknesses in one detector is not disclosed in the available prior art. The subject matter of claim 1 is therefore novel an involves an inventive step.

1.3 The other claims depend on claim 1 and therefore fulfil the requirements of Art. 33(2) and (3) PCT as well.

2 **Re Item VII**

2.1 The independent claim is not properly cast in the two part form, with those features which in combination are part of the prior art (see document D1) being placed in the preamble; therefore, the requirements of Rule 6.3 b) PCT are not met.

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET

International application No. PCT/IB99/01002

2.2 The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

2.3 Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the document D1 is not mentioned in the description, nor is this document identified therein.

CLAIMS:

1. A detector for ionising radiation comprising a first relatively thick layer of diamond material and a second relatively thin layer of diamond material adjacent to the first layer, the layers being connected electrically to a common contact, the first and second layers being optimised for the detection of different types of radiation or for the detection of different parameters of a particular type of radiation, with respective first and second contacts connected to the first and second layers, so that the detector simultaneously provides first and second output signals corresponding to radiation incident on the detector elements.

2. A detector according to claim 1 wherein the common contact comprises a metallic or semi-conductor layer between the first and second diamond layers.

3. A detector according to claim 2 wherein the common metallic or semi-conductor layer comprises a material selected from the group consisting of titanium, tungsten, molybdenum and boron doped diamond.

4. A detector according to any one of claims 1 to 3 wherein the first layer has a thickness of between 0.3 mm and 1.5 mm.

5. A detector according to claim 4 wherein the first layer has a collection distance of at least 20 μm.

6. A detector according to claim 5 wherein the first layer has a collection distance of at least 50 μm.

7. A detector according to claim 6 wherein the first layer has a collection distance of 300 μm or more.

8. A detector according to any one of claims 1 to 7 wherein the first layer is optimised for the detection of beta particles, x-rays and gamma rays.

9. A detector according to any one of claims 1 to 8 wherein the second layer has a thickness of between 10 μm and 40 μm.

10. A detector according to any one of claims 1 to 9 wherein the second layer is optimised for the detection of alpha particles.

11. A detector according to any one of claims 1 to 10 further including respective conductive layers on the outer surfaces of the first and second layers of diamond material.

12. A detector according to claim 11 wherein the conductive layers comprise a material selected from the group consisting of titanium, tungsten, molybdenum and boron doped diamond.

13. A detector according to claim 11 or claim 12 including respective active contacts connected to the conductive layers.

14. Radiation detector apparatus comprising a detector according to any one of claims 1 to 13, bias means arranged to apply respective bias voltages to the first and second diamond layers, and first and second amplifiers having inputs connected to the first and second diamond layers and arranged to generate respective first and second amplified output signals corresponding to radiation incident on the layers.

PATENT COOPERATION TREATY

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REC'D 21 JUL 2000

WIPO PCT

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference W/D/107	**FOR FURTHER ACTION** See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)	
International application No. PCT/IB99/01002	International filing date *(day/month/year)* 03/06/1999	Priority date *(day/month/year)* 08/06/1998
International Patent Classification (IPC) or national classification and IPC G01T1/26		
Applicant DE BEERS INDUSTRIAL DIAMOND DIVISION (PROPRIETARY)		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 5 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 2 sheets.

3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☐ Certain observations on the international application

Date of submission of the demand	Date of completion of this report
08/12/1999	19.07.2000
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Rabenstein, W Telephone No. +49 89 2399 2450

Form PCT/IPEA/409 (cover sheet) (January 1994)

I. Basis of the report

1. This report has been drawn on the basis of (*substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments.*):

Description, pages:

1-9	as originally filed	

Claims, No.:

1-14	with telefax of	07/07/2000

Drawings, sheets:

1/1	as originally filed	

2. The amendments have resulted in the cancellation of:

☐ the description, pages:
☐ the claims, Nos.:
☐ the drawings, sheets:

3. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

4. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-14
	No:	Claims	
Inventive step (IS)	Yes:	Claims	1-14
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-14
	No:	Claims	

2. Citations and explanations

see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

1 **Re Item V**

1.1 Reference is made to the following document:

D1: WO 97 00456 A (IMPERIAL COLLEGE ;HASSARD JOHN FRANCIS (GB); GODDARD ANTONY JOHN H) 3 January 1997 (1997-01-03)

1.2 The application relates to a detector for ionizing radiation comprising diamond as detector material. Such detectors are known and generally comprise a diamond layer sandwiched between two electrodes (see for example D1). A problem with the known detectors is that they do not allow to detect different types of radiation or different parameters of one kind of radiation, as they are generally optimized for the type of radiation to be measured. In one arrangement of D1, it is possible to detect at the same time slow and fast neutrons by using two separate detectors and covering one by a slow neutron filter.

The object underlying the present invention is to create a single device allowing simultaneous measurement of different types or different parameters of radiation. This is achieved by providing at least two diamond layers of different thicknesses on a common electrode. The only document relating to the detection of different parameters of radiation is D1, but this document requires two separate detectors and an additional filter. The use of diamond layers of different thicknesses in one detector is not disclosed in the available prior art. The subject matter of claim 1 is therefore novel an involves an inventive step.

1.3 The other claims depend on claim 1 and therefore fulfil the requirements of Art. 33(2) and (3) PCT as well.

2 **Re Item VII**

2.1 The independent claim is not properly cast in the two part form, with those features which in combination are part of the prior art (see document D1) being placed in the preamble; therefore, the requirements of Rule 6.3 b) PCT are not met.

2.2 The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

2.3 Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the document D1 is not mentioned in the description, nor is this document identified therein.

CLAIMS:

1. A detector for ionising radiation comprising at least first and second diamond detector elements connected electrically to a common contact, with respective first and second contacts connected to the first and second detector elements, so that the detector simultaneously provides first and second output signals corresponding to radiation incident on the detector elements.

2. A detector according to claim 1 wherein the first and second detector elements are optimised for the detection of different types of radiation.

3. A detector according to claim 1 wherein the first and second detector elements are optimised for the detection of different parameters of a particular type of radiation.

4. A detector according to any one of claims 1 to 3 wherein the first and second detector elements are formed as respective first and second layers of diamond material in contact with a common metallic or semi-conductor layer.

5. A detector according to claim 4 wherein the first layer comprises a relatively thick layer of diamond material and the second layer comprises a relatively thin layer of diamond material.

6. A detector according to claim 4 or claim 5 wherein the common metallic or semi-conductor layer comprises a material selected from the group consisting of titanium, tungsten, molybdenum and boron doped diamond.

7. A detector according to any one of claims 4 to 6 wherein the first layer has a thickness of between 0.3 mm and 1.5 mm.

8. A detector according to claim 7 wherein the first layer has a collection distance of at least 20 μm.

9. A detector according to claim 8 wherein the first layer has a collection distance of at least 50 μm.

10. A detector according to claim 9 wherein the first layer has a collection distance of 300 μm or more.

11. A detector according to any one of claims 4 to 10 wherein the first layer is optimised for the detection of beta particles, x-rays and gamma rays.

12. A detector according to any one of claims 4 to 11 wherein the second layer has a thickness of between 10 μm and 40 μm.

13. A detector according to any one of claims 4 to 12 wherein the second layer is optimised for the detection of alpha particles.

14. A detector according to any one of claims 4 to 13 further including respective conductive layers on the outer surfaces of the first and second layers of diamond material.

15. A detector according to claim 14 wherein the conductive layers comprise a material selected from the group consisting of titanium, tungsten, molybdenum and boron doped diamond.

16. A detector according to claim 14 or claim 15 including respective active contacts connected to the conductive layers.

17. A detector substantially as herein described with reference to the accompanying drawing.

18. Radiation detector apparatus comprising a detector according to any one of claims 1 to 17, bias means arranged to apply respective bias voltages to the first and second diamond detector elements, and first and second amplifiers having inputs connected to the first and second diamond detector elements and arranged to generate respective first and second amplified output signals corresponding to radiation incident on the detector elements.

19. Radiation detector apparatus substantially as herein described with reference to the accompanying drawing.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference W/D/107	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/IB 99/01002	International filing date *(day/month/year)* 03/06/1999	(Earliest) Priority Date *(day/month/year)* 08/06/1998
Applicant DE BEERS INDUSTRIAL DIAMOND DIVISION (PROPRIETARY)		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 4 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.
      [ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).
   b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :
      [ ] contained in the international application in written form.
      [ ] filed together with the international application in computer readable form.
      [ ] furnished subsequently to this Authority in written form.
      [ ] furnished subsequently to this Authority in computer readble form.
      [ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
      [ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).
3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title**,
   [X] the text is approved as submitted by the applicant.
   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   [ ] the text is approved as submitted by the applicant.
   [X] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is Figure No. 1
   [X] as suggested by the applicant.
   [ ] because the applicant failed to suggest a figure.
   [ ] because this figure better characterizes the invention.
   [ ] None of the figures.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB 99/01002

Box III TEXT OF THE ABSTRACT (Continuation of item 5 of the first sheet)

The abstract is modified as follows:
Line 1: after "first" insert "(10)" ;
Line 1: after "second" insert "(12)" ;
Line 2: after "contact" insert "(14)".

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 99/01002

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01T1/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 97 00456 A (IMPERIAL COLLEGE ;HASSARD JOHN FRANCIS (GB); GODDARD ANTONY JOHN H) 3 January 1997 (1997-01-03) abstract column 3, line 23 - column 4, line 13 column 5, line 31 - column 6, line 18 column 7, line 1 - column 8, line 7 column 13, line 4 - line 12 figures ---	1,2, 17-19
A	US 3 450 879 A (SEPPI EDWARD J) 17 June 1969 (1969-06-17) column 1, line 51 - line 65 column 2, line 49 - line 54 column 3, line 26 - line 42 figures --- -/--	1,4, 17-19

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 August 1999	17/08/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Datta, S

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 99/01002

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 381 517 A (DE BEERS IND DIAMOND) 8 August 1990 (1990-08-08) abstract column 1, line 46 - column 3, line 11 figures -----	1

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/IB 99/01002

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 9700456	A	03-01-1997	AU	6009696	A	15-01-1997
US 3450879	A	17-06-1969	NONE			
EP 0381517	A	08-08-1990	AU	619949	B	06-02-1992
			AU	4902790	A	09-08-1990
			CA	2009178	A,C	03-08-1990
			DE	69006224	D	10-03-1994
			DE	69006224	T	05-05-1994
			JP	2080186	C	09-08-1996
			JP	2291178	A	30-11-1990
			JP	7120813	B	20-12-1995
			US	5055686	A	08-10-1991

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
G01T 1/26, 3/08

A1

(11) International Publication Number: **WO 97/00456**

(43) International Publication Date: 3 January 1997 (03.01.97)

(21) International Application Number: PCT/GB96/01357

(22) International Filing Date: 6 June 1996 (06.06.96)

(30) Priority Data:
9512057.2 14 June 1995 (14.06.95) GB

(71) Applicant *(for all designated States except US)*: IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY & MEDICINE [GB/GB]; Exhibition Road, London SW7 2AZ (GB).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: HASSARD, John, Francis [GB/GB]; Selkirk Hall, Princes Gardens, London SW7 1LU (GB). GODDARD, Antony, John, Hudson [GB/GB]; 20 Maze Road, Kew, Surrey TW9 3DE (GB).

(74) Agents: MAGGS, Michael, Norman et al.; Kilburn & Strode, 30 John Street, London WC1N 2DD (GB).

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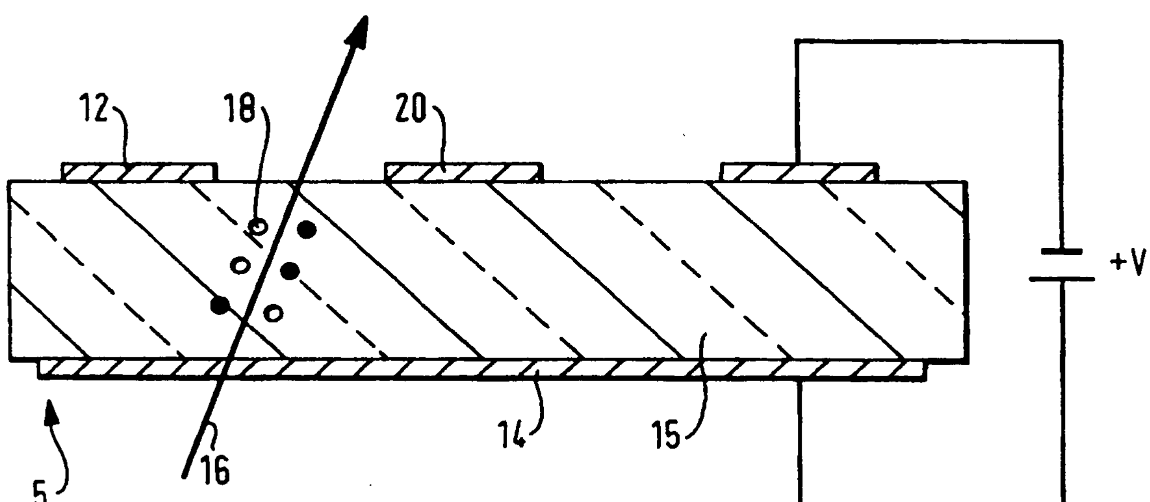
(54) Title: NEUTRON DETECTOR



(57) Abstract

A neutron detector (5, 10) comprises a diamond detector element (15, 40) doped with boron. Boron-doped diamond substantially improves the rate of neutron detection due to the large amount of pair production, and is extremely mechanically and thermally robust. In one embodiment (15) of the invention, the detector is planar. A second embodiment (10) uses a series of ridges (40) and improves the response rate still further; the incident neutron energy, position and time of incidence upon the detector is also enhanced in comparison with prior art detectors. The detector finds particular application in the field of slow (thermal) neutron detection, but is nonetheless useful in fast neutron spectroscopy.

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Neutron Detector

This invention relates to a neutron detector.

The problem of how to detect neutrons has concerned workers in the fields of reactor physics, health physics and academic research for some time. The neutrons, which are uncharged particles, can only be detected by their interaction with charged particles such as protons or light nuclei. One such reaction is:

$$Li_3^6 + n - Li_3^{7*} - H_1^3 + He_2^4$$

The problem with using lithium to detect neutrons is that it cannot be made into a solid state detector, predominantly because of its high volatility. Other elements that have also been used to attempt to detect neutrons and use a similar mechanism to the neutron-to-triton mechanism above are He^3 (which must also be used in gaseous form), N^{14}, S^{32} and Cl^{35}. The spatial, temporal and energy resolutions of known neutron detectors remain substantially poorer than corresponding charged particle detectors. Measuring the energy of an individual neutron is extremely difficult, and even simply detecting the presence of neutrons poses problems which known detector materials have not adequately solved. Furthermore, it is extremely difficult using known neutron detectors to measure the time of incidence of a neutron, a problem which is related to the energy measurement if one considers the time-of-flight. Further, in the non-destructive testing technique known as neutron radiography, it is currently impossible to devise a neutron detector which has both a high spatial resolution and a very fast dynamic response.

It is an object of the present invention to provide a neutron detector whose detection properties are superior to those of the prior art.

According to the present invention there is provided a neutron detector comprising a plurality of boron-doped diamond detector elements having generally parallel sides, the sides carrying readout electrodes.

The combination of the shape and constitution provides a detector that is relatively cheap to manufacture, is highly sensitive, has an extremely fast response time (less than 50 picoseconds), and provides very accurate positioning information without significant cross-talk between channels. The energy and time of incidence of the neutron are also measurable with some precision. In contrast to a planar geometry, the parallel sides of the detector allow excellent containment of the products of interaction between the boron-doped diamond and the neutrons.

In addition, this topography has a directional response which is dependent upon the aspect ratio of the height of the parallel walls to the gap between them. By varying this ratio, the detector's response may be made more or less dependent on the angle of incidence of the incident neutrons.

Boron acts as a substitutional acceptor. The diamond lattice is able to accept an extremely large concentration of boron, which has a huge capture cross section for neutrons (approximately 7.5×10^{-22} cm^2) but a relatively small scattering cross section (4×10^{-24} cm^2). In addition, a large amount of energy is released upon neutron capture, allowing ready detection over a wide

range of energies.

The detection occurs through the reaction:

$$B_5^{10} + n \rightarrow B_5^{11*} \rightarrow Li_3^7 + He_2^4$$

and the alpha particle is readily detected by its production of electron-hole pairs which are collected by the readout electrodes. Both reaction products, however, are capable of generating an easily resolvable signal against which the presence of other radiations can be discriminated. B^{10} occurs at the level of about 20% of naturally occurring boron, but may be extracted to produce essentially isotopically pure B^{10}. Alternatively, doping with B^{11} may be considered.

Since diamond is the subject of the boron doping, other advantages over the prior art such as excellent mechanical and thermal robustness together with radiation hardness are achieved. Boron triflouride gas filled counters will detect neutrons using a similar reaction to that above, but suffer from effects of dampness or vibration and require regular maintenance.

The boron concentration is preferably 10^{20} atoms cm^{-3} or less, for example less than 10^{17} atoms cm^{-3}. Diamond doped with about 10^{20} atoms cm^{-3} of boron is known as type IIB diamond and appears slightly blue owing to absorbtion in the violet and blue regions of the visible spectrum. Once the boron concentration rises substantially above 10^{18} atoms cm^{-3}, increased dark current leakage (noise) occurs and the diamond becomes a semiconductor. There is a trade off between increased noise in the detector at high concentrations of boron and reduced sensitivity to incident neutrons (due to reduced total integrated cross

section) at lower concentrations.

Preferably, the detector element is formed by a growth method including hot filament chemical vapour deposition (HFCVD) or microwave or radio frequency plasma growth chemical vapour deposition. The quantity of boron may be controlled to quite precise values, for example by employing diborane gas (B_2H_6) or boric acid in acetone.

Alternatively, the boron may be ion-implanted into type IIA diamond. This is most preferably carried out using an ion concentration of 10^{14} atoms cm^{-2} and ion beam energy of 40 keV.

The present invention can be put into practice in various ways which will now be described by way of example with reference to the accompanying drawings in which :-

Figure 1 shows a double logarithmic plot of capture cross-section against neutron energy for boron-doped diamond;

Figure 2 shows a sectional view of a planar neutron detector according to a first embodiment of the present invention;

Figure 3 shows a perspective view of a ridge detector for detecting neutrons according to a second embodiment of the present invention; and,

Figure 4 shows a partial cross section along the line P-P′ of Figure 3.

Figure 1 indicates the manner of interaction of neutrons

with boron. When the incident neutron energy is 0.01 eV, the capture cross section is $1.1x10^{-21}$ cm^2, at 1 eV it is $1x10^{-22}$ cm^2, and at 1 keV it is $4x10^{-24}$ cm^2. The total capture cross section of a neutron in boron is thus inversely proportional to the velocity of the neutron, as is indicated by the negative slope of the log-log plot of Figure 1. A further remarkable feature of boron is the lack of a resonant peak in the cross-section vs. energy plot, suggesting that the signal produced is a linear function of neutron energy.

Diamond may be doped with boron using a number of well-known methods. One technique is to grow a crystal epitaxially either in a microwave/radio frequency plasma, or use hot filament chemical vapour deposition (HFCVD). Alternatively, a pre-formed type IIA diamond may be ion-implanted with boron, using a typical dose of 10^{14} ions cm^{-2} and beam energy of around 40 keV. The activation energy of a heavily doped diamond sample (10^{20} atoms cm^{-3}) is approximately 2 meV. At this level of doping, the dark current noise - that is, the level of "background" current produced even when there are no incident neutrons - is dramatically increased. For this reason, there is a trade off whereby increasing the doping raises the sensitivity but increases the dark current.

In the growth methods outlined above, the quantity of boron is controlled in a straightforward manner by using gases such as diborane (B_2H_6) or boric acid in acetone.

Figure 2 shows a planar neutron detector 5 comprising a flat sheet 15 made of boron-doped diamond. The doping may be by B^{10} or B^{11}. This sheet 15 has thin gold electrode coatings 12,14 on its upper and lower surfaces. The upper electrode coating 12 comprises a plurality of

parallel readout strips which are aligned in a direction perpendicular to the plane of the paper in the Figure, and the lower electrode coating 14 comprises a further plurality of readout strips aligned in a direction parallel with the plane of the paper. A large potential difference V is maintained between the electrode coatings.

A neutron following a path 16 through the boron-doped diamond produces excited boron atoms which rapidly decay into stable lithium atoms and alpha particles. These in turn produce electron-hole pairs 18,20, which separate under the influence of the electric field and induce a charge on the readout strips. The energy of the neutron can be determined by the amount of charge which is collected, and its position by the intersection of the upper and lower strips receiving the largest induced charges. High precision is obtained because of the large number of electron-hole pairs produced: for example, a 1 MeV alpha particle produced during the nuclear reaction will in turn produce in excess of 100,000 electron-hole pairs.

Using boron-doped diamond confers significant advantages over prior art planar neutron detectors in terms of increased sensitivity, ability to detect larger numbers of neutrons, and improved energy and time resolution. For example, undoped diamond has a relatively poor charge collection efficiency due to limits imposed by the charge intrinsic lifetime within the diamond. Nonetheless, it is sometimes advantageous to employ less heavily boron-doped diamond in order to limit the otherwise unmanageable count rate of the detector.

In order further to improve the detector characteristics,

however, the ridge arrangement of Figures 3 and 4 may be employed. Here, the detector comprises a boron-doped diamond substrate 30 having, on one surface, a plurality of parallel etched boron-doped diamond ridges 40. On one side of each ridge there is a positive readout electrode 50, and on the other side a negative electrode 60. These are preferably conductors, but could instead be of a high-conductivity doped semiconductor material.

In use, the detector is positioned in line with a source of neutrons 70 to be detected. If it is desired to detect fast neutrons, the substrate is aligned substantially normal to the direction of the neutron beam. An individual neutron passing into one of the ridges creates lithium atoms and alpha particles which in turn produce electron-hole pairs. These rapidly migrate to the electrodes 50,60 by virtue of the potential difference which is maintained between them and which is of order 1 V μm^{-1} in the "C" direction. Charge is thereby induced on the electrodes, this charge being read off by readout devices (not shown) at the ends of the ridges. Once again, the large numbers of electron-hole pairs produced are advantageous, and can further be registered with excellent noise discrimination in the present embodiment.

The substrate and ridges may preferably be grown using one of the techniques outlined above. The ridges may either be grown with the substrate, or they may be etched (for example with an excimer laser). The electrodes 50,60 may be of any suitable ohmic material, such as gold, platinum, titanium, chromium and so on. Standard deposition techniques may be used to apply the metal as a thin coating to the sides of the ridges. Typically, the device may be made by etching the ridges, depositing the material, and then polishing the top surface.

It will be appreciated from Figure 4 that the sensitivity of the device shown can be increased by making the value of D (or the height of the ridges) larger. The greater the height of the ridges, the larger the amount of material which a neutron has to pass through, thereby increasing the number of interaction products within the device. The readout speed and charge collection efficiency is determined substantially by the width C of each of the ridges. Depending upon the particular application, the value of C may be as little as a few micrometers, and the value of D 100 micrometres or more, preferably in excess of 200 micrometres. Grater thicknesses provide greater efficiency as they increase the integrated boron cross-section faced by the incoming neutron. The signal-to-noise ratio is large, as there is negligible cross-talk between signals emanating from individual ridges. This is because the leakage current is low which in turn minimises shot noise. The associated read-out electronics also contribute little noise even when the signal is integrated over very short time periods (e.g. between 10 and 5000 nanoseconds). A typical substrate depth is around 100 micrometres, sufficiently thick to support the ridges and to be free-standing without requiring an additional supporting base. Ideally, the substrate and the ridges are together formed from a single wafer of material.

The directionality of the response of the ridge-shaped detector may be tailored to suit the application for which the detector is to be used. This is because the sharpness of response as a function of angle depends upon both the aspect ration B/C in Figure 4, together with the "coverage" defined as the ratio C/(C+A).

The impedance of the readout devices (not shown) at the

end of the ridges is preferably matched with the impedance of the electrodes 50,60, thereby increasing readout speed and reducing signal losses.

In order further to improve the neutron detecting capability of the detector, the spaces between the ridges may be filled with a plastics material, or other absorber.

In a further embodiment (not shown) a further parallel set of ridges, orthogonal to the first set, is provided on the lower surface of the substrate 30.

The ridge shaped neutron detector described above can provide extremely rapid charge readout, probably within 35 ps and certainly within 50 ps. These readout speeds cannot currently be achieved for any single pulse detector of comparable sensitivity and positional accuracy. In addition, the positional resolution is better than 20 μm (and probably better than 10 μm); resolution is determined by the size of the ridge top C in Figure 3.

The signal detected by the electrodes may be read out by any conventional readout electronics. In one arrangement, the pulses of electric charge deposited by the nuclear process involved may be detected as a current (in dosimetry applications, for example). Alternatively, some applications may require the detection of single neutrons (for example in radiological applications), and this may be achieved by means of suitable electronics running in charge mode. It is a particular novel feature of the detector described above that it may either be operated as a dosimeter, or as a single neutron detector, according to application.

A 1 cm^3 array of diamond doped with 10^{20} atoms cm^{-3} of boron will have a total capture cross section of 7.5×10^{-22} cm^2. When a flux of thermal (slow) neutrons having an energy of 25 meV is incident upon this, calculations suggest that at least 7.5% of the incident neutrons are detected. This is well in excess of the corresponding detection rate of prior art detectors.

Further, since the neutron interaction produces alpha particles, the signal in the detector will be very large; both the alpha particle and the lithium atom produced by the neutron's interaction with boron will travel very short distances (of order a few nm for Li, and a few μm for the alpha particle). Even over this short range, the products may produce in the region of 180,000 electron-hole pairs, depending on the incident neutron energy.

It may be desirable in some applications to reduce leakage by cooling the detector.

In one embodiment the boron-doping is restricted to a thin surface film. This may coat the upper surface of the ridges which may themselves be of intrinsic diamond. The coating may be of any suitable boron-rich substance such as borate. Preferably, the boron-rich coating should be thinner than the range of the emitted alpha particles, for example less than 20 μm. In yet another alternative arrangement, boron may be layered in a sandwich structure within the ridges.

Boron-doped diamond as described above has a number of apparent applications, such as in monitoring devices, particularly in and around nuclear reactors and nuclear chemical plants (where it is essential to be warned of

the onset of accidental criticality). Further applications are envisaged in detection devices, such as analysis of radioactive waste, fissile material safeguards (where the level of radiation may be relatively low) and neutron thermopiles. The unusual properties of boron doped diamond make it particularly advantageous when used in the latter application, where the environment may be hot and hostile. In a reactor, the background from gamma radiation and other ionising particles may be removed by using a "double electrode" technique, or by simply gating the huge pulse produced by a neutron. The low cross section for gamma radiation interaction with diamond is therefore an advantage in the present case, and permits a counting rate and range substantially higher than that in known reactor power level monitors such as fissile detectors.

Boron-doped diamond also has substantial applications in diagnostic devices which detect and interrogate backscattered neutrons, for example in substances containing carbon or hydrogen. The backscattering medium acts in essence as a moderator, its low mass making scattering particularly effective since scattering depends exponentially upon the mass of the scatterer.

Thus by using the detector in combination with a rapid pulse source or an electronic chopper, it is possible to detect and interrogate drugs; this is possible because of the excellent time-of-flight and energy resolution capabilities of the detector. The high resolution and penetration capabilities also allow the detection of explosives and plastic explosives in particular, since they are constituted of materials having low atomic numbers. Finally backscattering of hydrocarbons may be interrogated, the thermal, radiological, chemical and

mechanical robustness of diamond being beneficial. Since the detector does not need a window, sensitive measurements down a bore-hole, for example, are possible.

The boron-doped diamond detector, being relatively compact, is especially suited to applications in the fields of continuous area monitoring and personal dosimetry. Small devices capable of detecting other forms of radiation are already known and can be incorporated with the boron doped diamond neutron detector. For example, to measure tissue dose over a wide range of energies, the detector must give an energy dependent dose response equivalent to that of human tissue. This may be done by using layers of polythene and screening materials together with the doped diamond.

The ridge-type detector with its spatial resolution (and the further embodiment with the perpendicular set of ridges which allows x-y positioning), together with the very rapid time response and high sensitivity, renders the detector suitable for novel applications in neutron radiography. In particular, it offers the possibility of neutron radiography of either static or dynamic systems containing moderating material of a smaller size and a more rapid dynamic response than has hitherto been possible. In neutron radiography, a parallel beam of neutrons impinges on the engineering component (containing some included moderating material). Any collision with this moderating material diverts the neutron from the parallel beam - effectively throwing an image of the system, highlighting the moderating material, upon a detector.

Although boron-doped diamond is of particular use in detecting slow neutrons, it will also detect fast

neutrons. For example, in neutron time and flight measurements, a fast response time together with high detection efficiency is required over all neutron energies. A number of planar boron-doped diamond detectors may be employed adjacent to one another, thereby increasing the area presented to the neutrons. This system improves upon known detectors such as lithium glass scintillators. By providing two diamond detectors, one of which is covered by a slow neutron filter such as a cadmium screen, it is possible to determine both the total number of neutrons incident as well as the respective amounts of slow and fast neutrons.

Another use is in neutron spectroscopy and neutron diffraction. A thin layer of material containing lithium or He^3 might be placed between two diamond detectors. The reaction of the neutron with the lithium then produces a triton and an alpha particle. The fast detection rate of the diamond aids coincidence detection, whilst the summing of the two particle responses may be interpreted to yield the neutron energy.

Finally the use of the so-called "proton recoil" principle may also allow doped diamond to detect fast neutrons. A suitable proton-containing radiator would be used and the proton energy measured at a range of angles.

CLAIMS

1. A neutron detector comprising a plurality of boron-doped diamond detector elements having generally parallel sides, the sides carrying readout electrodes.

2. A neutron detector as claimed in claim 1, wherein the boron concentration is 10^{20} atoms cm^{-3} or less.

3. A neutron detector as claimed in claim 2, wherein the boron concentration is 10^{18} atoms cm^{-3} or less.

4. A neutron detector as claimed in claim 3, wherein the boron concentration is between 10^{18} atoms cm^{-3} and 10^{16} atoms cm^{-3}.

5. A neutron detector as claimed in any preceding claim, wherein the detector element is formed by a growth method including chemical vapour deposition (CVD) or microwave or radio frequency plasma growth.

6. A neutron detector as claimed in claim 5, wherein the boron is introduced to the diamond using diborane (B_2H_6) gas or boric acid in acetone.

7. A neutron detector as claimed in any one of claims 1 to 4, wherein the diamond is doped by ion implantation of boron into type IIA diamond.

8. A neutron detector as claimed in claim 7, manufactured by an ion beam of concentration is 10^{14} atoms cm^{-2}.

9. A neutron detector as claimed in any one of the

preceding claims in which the plurality of detector elements are formed from a single wafer of diamond.

10. A neutron detector as claimed in any one of the preceding claims in which the detector elements comprise non boron-doped diamond having a boron-rich coating thereon.

11. A neutron detector as claimed in claim 10 in which the coating is of borate.

12. A neutron detector as claimed in any one of claims 1 to 9 in which the detector elements comprise a sandwich structure of boron-doped and non boron-doped diamond.

13. A neutron detector as claimed in any one of the preceding claims in which the detector elements are mutually parallel, the space between adjacent elements being filled with an absorber material.

14. A neutron detector as claimed in any one of the preceding claims having a first detector element which is filtered by a slow-neutron filter, and a second exposed detector element.

15. A neutron detector as claimed in claim 11 in which the filter is of cadmium.

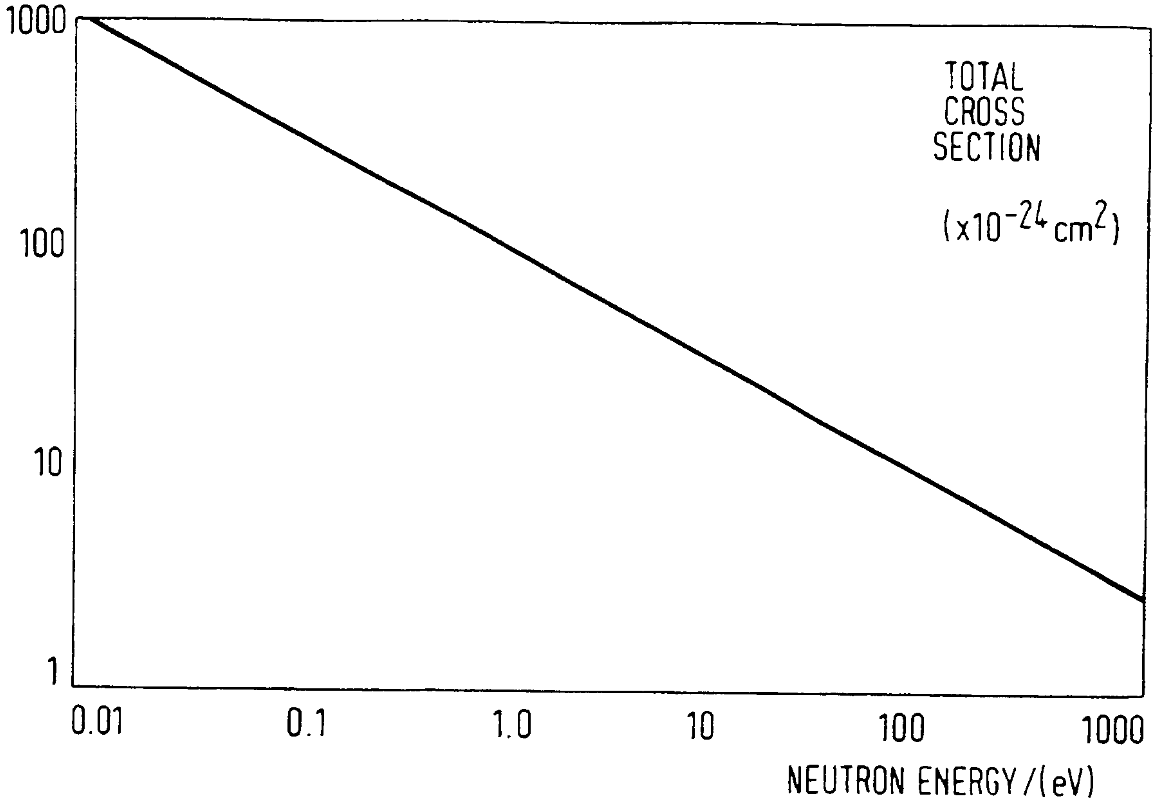
16. A neutron detector as claimed in any one of the preceding claims including an adjacent layer of a material containing lithium.

17. A neutron detector as claimed in any one of the preceding claims including an adjacent layer of a

material including He^3.

18. A neutron detector as claimed in claim 13 or claim 814 in combination with a further neutron detector, the layer being sandwiched between the to detectors.

19. A neutron detector substantially as specifically described with reference to figure 2 or with reference to figures 3 and 4.


1000
100
10
1
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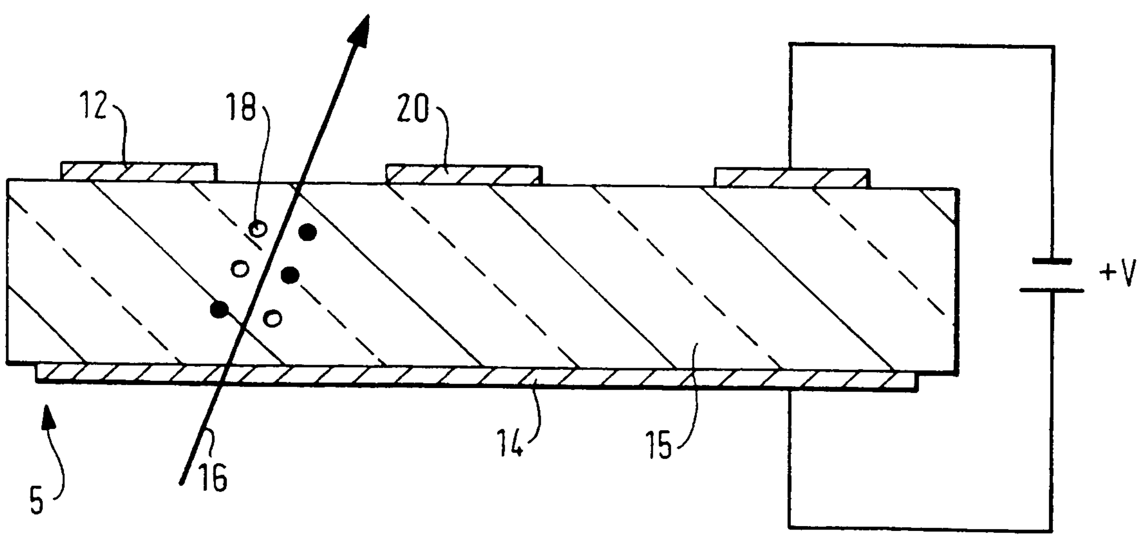
1.0
10
100
1000
NEUTRON ENERGY/(eV)

FIG. 1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14
15

FIG. 2

2/2

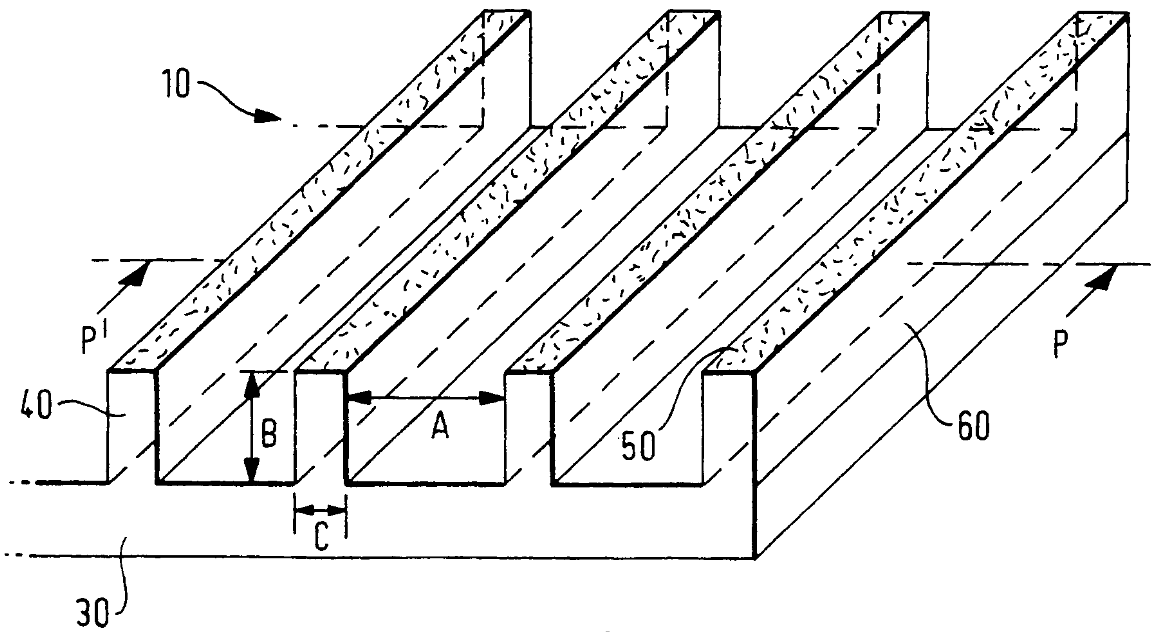

FIG. 3

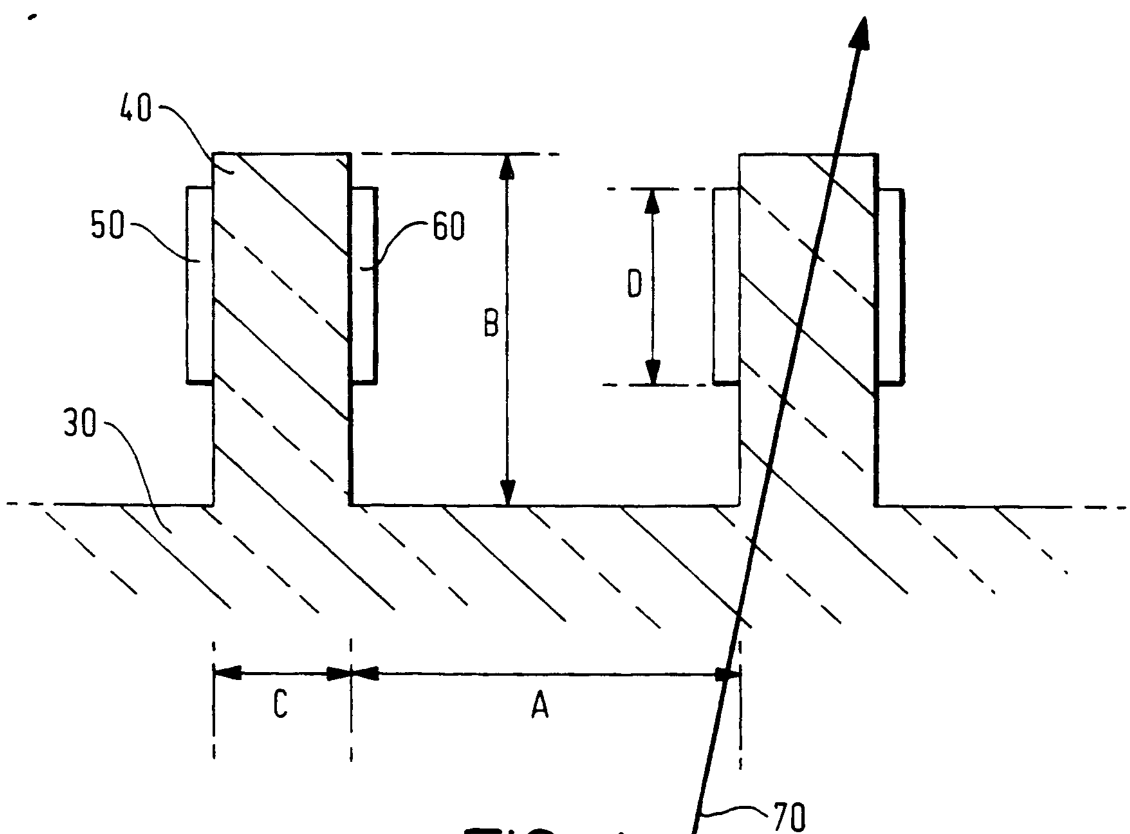

FIG. 4

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/01357

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01T1/26 G01T3/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	WO,A,96 04572 (IMPERIAL COLLEGE ;HASSARD JOHN FRANCIS (GB); CHOI PETER (GB)) 15 February 1996 see abstract see page 4, line 2 - page 5, line 8 see page 8, line 4 - page 11, line 28 see figures ---	1,5,6,9, 10,13,19
Y	EP,A,0 479 625 (DE BEERS IND DIAMOND) 8 April 1992 see abstract see column 2, line 7 - line 40 see column 3, line 31 - column 4, line 56 see claims 1,3-5 see figures --- -/--	1,5,6,9, 10,13,19

[X] Further documents are listed in the continuation of box C.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
18 September 1996	20.09.96
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Authorized officer Datta, S

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International Application No
PCT/GB 96/01357

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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